MEASUREMENT OF THE ANGLE OF ARRIVAL OF DOWNCOMING WAVES FROM INDIAN REGIONAL SHORT-WAVE STATIONS

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Plates IX and X

ABSTRACT. Results of the measurements of downcoming angles carried out at Delhi on signals radiated from the Bombay and Madras broadcasting stations of All-India Radio are given and discussed. Close agreement has been found between the experimental and the theoretical values. Use of pulse signals radiated from these stations made it possible to resolve the downcoming waves into their component waves and to determine the downcoming angles of each. The results provide an interesting study of the importance of the various parameters which may control propagation under given conditions. The role of the intervening ionized strata such as the E-layer is also analysed and discussed.

INTRODUCTION

The importance of a knowledge of the angle of arrival of short-waves propagated *via* the ionosphere has been pointed out in an earlier paper.[1] The present programme of work was undertaken to analyse the propagation conditions that prevail in the case of transmissions from the regional short-wave transmitters of All-India Radio. As will be apparent from a study of the results presented in the text, use of pulse signals not only helped to overcome the difficulty experienced in connection with the agitation and haphazard rotation of the patterns appearing on the cathode-ray oscillograph screen, but also helped to resolve the downcoming waves into their various components, thus providing direct information regarding the extent and importance of the various modes of propagation prevailing at any time. The use of pulse signals for downcoming angle measurements is therefore a very potent and vigorous method of attack for obtaining information on short-wave propagation.

HISTORICAL

Various methods of measurement have been adopted by previous workers in this field of downcoming angle measurements, some of the notable workers among them being Friis,[2] Eckersley,[3] Hollingworth,[4] Friis, Feldman and Sharpless,[5] Wilkins,[6] Crone, Kruger, Goubau and Zenneck,[7] Eyfrig,[8] Edwards,[9] and Chamanlal.[1] Here the various methods are described briefly. Friis used two vertical aerials spaced one-third of a wavelength apart to collect the signal and used a C.R.O. for measuring the phase difference. The method employed by Hollingworth consisted in recording simultaneously the signals picked up on a vertical aerial and a loop aerial with its plane in the plane of propagation. It can be shown that ratio of the e.m.f. developed in the vertical aerial to that in the loop is proportional to the cosine of the angle of incidence measured to the horizontal. Also instead of recording signal strengths, he employed two amplifiers the gains of which were adjusted to give a null on a galvanometer when connected differentially to the outputs of the amplifiers. The ratio of the outputs of the amplifiers would then give the cosine of the angle of incidence. Eckersley used another development of the vertical and loop aerial. Wilkins, and recently Chamanlal employed the method developed by the Radio Research Board of England. It consists essentially in measuring the phase difference set up in two similar and parallel horizontal aerials with their centres in the great circle path of the transmitter and with their axes at right angles to it. A C.R.O. is used for measuring the phase difference. Friis, Feldman and Sharpless employed primarily two methods known as (*i*) the Differential output method, and (*ii*) the Phase method. In the differential output method, they employed two horizontal aerials with different heights above the ground to give a contrasting directional pattern in the vertical plane and the outputs were recorded simultaneously on integrating field-strength recorders and the ratio of the output was the measure of the downcoming angle. In the phase method, two vertical aerials spaced apart in the great circle path between transmitter and receiver were used and the difference in phase set up was either measured by inserting a calibrated phase adjuster in one of the limbs and adjusting for balance or measured on the C.R.O. in the usual way. Edwards and Jansky used the very elaborate musa system with an array of rhombic antennae.

The present method is the same as used by Chamanlal [1] in the determination of the downcoming angles of foreign short-wave stations. This method is adopted for two reasons. It is easy to set up, and it works admirably well on pulse signals. With the help of a C.R.O., it is possible to resolve the wave into its component rays and to measure their downcoming angles simultaneously.

THEORY

The basic principle underlying the method is illustrated in Fig. 1.

A and B are two parallel horizontal aerials and EA is the direction of the downcoming ray making an angle θ to the horizontal. The phase difference set up as a result of the path difference AF is given by :

$$\varphi = \frac{2\pi d}{\lambda} \cos\theta \cos\psi \text{ radians,}$$

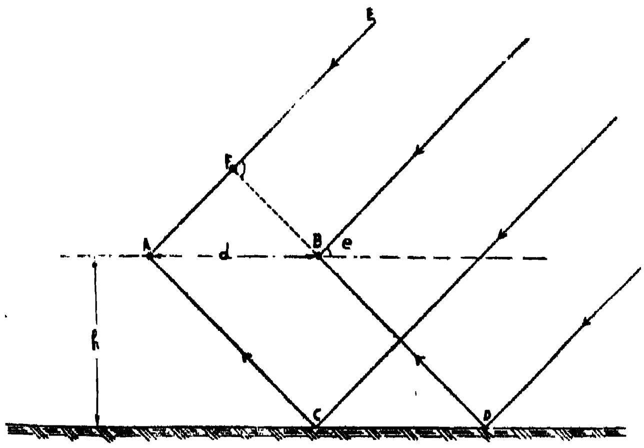


FIG. 1

where d = Spacing in metres between the two parallel aerials.

λ = The wave-length in metres of the wave under investigation.

θ = The downcoming angle of the incident wave measured to the horizontal.

ψ = The angle between the direction of the transmitting station and the line joining the centres of the aerials.

It can be shown that in a homogeneous field the effect of the ground will be similar for both the aerials. Though it might affect the signal strength, it does not alter the phase relationship. θ, the downcoming angle, can be calculated if ϕ is measured.

The requisite part of the experiment is the correct measurement of this phase difference. When the e.m.f.'s of the aerials are fed to the opposite pairs of plates of the C.R.O., an ellipse is formed. If the two e.m.f.'s are equal, the major axis of the ellipse will be inclined at an angle of 45° to the axes of the C.R.O. screen and the eccentricity of the ellipse is dependent upon the phase difference between the two e.m.f.'s. However the aerial outputs are to be considerably amplified before a suitable deflection can be obtained on the C.R.O. For this purpose amplifiers are used.

THE EXPERIMENTAL SET-UP

The set-up is essentially the same as was used by Chamanlal [1] in his earlier work. Therein the set-up and the technique of measurement are dealt with in detail. Here only a brief description need be given.

Two horizontal doublet aerials 12 feet high, cut for the proper wave-length and spaced suitably, are used as signal collectors. The outputs are taken through twisted flex feeders on to a 'Receiving hut.' In the hut, are housed the shielded aerial switching panel and the amplifier assembly. The amplifier assembly consists of two commercial receivers, each receiver consisting of two stages of R.F. amplification and five stages of I.F. amplification. The local oscillators in the receivers are made inactive. An external oscillator replaces them and feeds both the receivers similarly and in the same phase. This ensures that the same phase relationship is passed on from the R.F. to I.F. stages. The outputs of the final I.F. amplifiers are fed to the opposite pairs of the plates of the C.R.O. The aerial switching panel consists of two shielded double-pole double-throw switches connected in such a way that any one of the two receivers can be connected to any of the two aerials separately or together.

PROCEDURE

The desired station is tuned in by means of the heterodyning oscillator and by setting the receivers approximately to the desired station. The same aerial is connected to both the receivers. Then the finer tuning is made by the help of the C.R.O. for maximum deflection. By slight adjustment of the tuning condenser and R.F. gain controls of the receivers, the trace on the C.R.O. is made into a line inclined at 45° to the horizontal and vertical axes. In this condition the receivers will have the same gain and zero phase difference. All that is then necessary is to put the two receivers on independent aerials and record the resultant ellipse. The resultant ellipse should not change its size or shape by interchanging the aerials. It however does change under improper conditions.

The improper conditions arise due to the input impedance conditions not remaining the same when the two receivers are connected in parallel to the same aerial as when they are connected independently to two separate aerials. In this case when the two receivers are connected in parallel and adjusted for zero phase and then changed over to independent aerials, the change in input impedance introduces a certain error which manifests itself as an extra phase difference. This extra phase difference adds up in one case and subtracts in the other from the incoming phase, when the aerials are interchanged. The change of shape of the ellipse noticed is due to this. It is obvious that the correct phase difference is the mean of the two. If, however, the extra phase introduced is large, the results become complicated. Taking for instance a case where the phase difference set up between the aerials is only 10° while the impedance error is say 20°, the eccentricity of the ellipses appearing on the C.R.O. will be $10^\circ \pm 20^\circ$, *i.e.*, -10° and 30°. An ellipse of a phase difference -10° means the same as the one of 10°. Thus the ellipses are of 10° and 30° eccentricity and the mean of the two gives a value of 20° which is erroneous. With a view to correct this, the input circuits in the earlier work [1] were made resistive by connecting very low value resistances across the inputs. This, however, reduces the gains considerably. In the present set-up the problem is solved slightly differently. The two receivers, particularly their input circuits, are aligned very carefully by means of a sweep frequency oscillator. This alignment is carried out right on the working band itself to ensure absolute identity. It was found by this that no extra phase error is introduced because the two input circuits being identical are affected equally. Any slight error that may creep in will be accounted for by taking the mean of the two values. This improvement over the previous method gave greater sensitivity to the receivers and better definition to the ellipses.

BEHAVIOUR AND INTERPRETATION OF THE ELLIPSES APPEARING ON THE C.R.O. SCREEN

Under actual working conditions it was observed that the two regional stations, Bombay and Madras, seldom gave ellipses that were sufficiently steady for downcoming angle measurements. The ellipses were often found to rotate, and change their size and shape in a haphazard manner. It was the worst in the mornings and the nights when multiple reflections were many. During the noon and early evening they were steadier. Mention is to be made of Madras signals in the early evenings. When Madras was working on 60 metres the signals were extremely steady though poor and the ellipse on the C.R.O. hardly changed its eccentricity. The pulse transmission at this time gave a single return indicating single ray transmission.

USE OF PULSE SIGNALS

This unsteady nature of the ellipse is known to every worker in this field and is correctly ascribed to energy being received in more than one direction in the vertical plane. (Friis, Feldman and Sharpless are probably the first to bring into use the pulse signals for downcoming angle measurements.) If the transmitter sends out short duration pulses instead of a steady carrier, the incident wave could be resolved into component rays. Each pulse signal sent out, travelling by several different paths or different numbers of reflections, would arrive at the receiving end as a succession of pulses, each characterised by its time-delay and by its angle of arrival. These characteristics are made use of to study the component rays separately.

In the present case pulses were radiated at a rate of 50 per second, each occupying about ·0004 second. The pulse signals are received in the same way as the carrier, with this difference that the receiving equipment is suitably modified. Pulse reception calls for wide-band receivers. This was achieved by modifying the equipment by introducing resistances in the tuned circuits of the I.F. stages, thus flattening out their response characteristics.

Typical patterns of the succession of pulses received at Delhi from Bombay and Madras broadcasting stations are given in plates IX and X. They give information on the time-delays suffered by each ray and they also show the energy distribution in the component rays of an incident wave. This will be dealt with more fully later. Such patterns are obtained by tuning in the pulse signals on one of the dual-receivers and applying the amplified signals to the vertical deflecting plates of the C.R.O., to the horizontal deflecting plates of which is applied a linear time base of 50 cycles per second and synchronized with the pulse frequency. If, however, to the horizontal plates, the signals from the other receiver are applied instead of the linear time base, ellipse patterns such as the ones shown in plate X are obtained. The ellipses formed will be equal in number to the number of component pulses, the size and eccentricity of each depending upon the amplitude and downcoming angle respectively of the component pulses.

The pulse-pattern and the ellipse-pattern combined give all the necessary information.

In practice, the method adopted for recording the pulse and ellipse-patterns is to take a series of photographs of each by means of a camera. The pulse-patterns could be switched over to the ellipse pattern by operating a switch.

The calculation of the downcoming angle from the eccentricity of the ellipse is then a simple matter. This was discussed fully in the earlier paper referred to before.

RESULTS

The results cover a period of eight months from 27th February, 1941, to 12th November, 1941. They are presented in a tabular form (Table I) giving the most common downcoming angles obtained during the period of measurements for the various transmissions. The actual mode of propagation

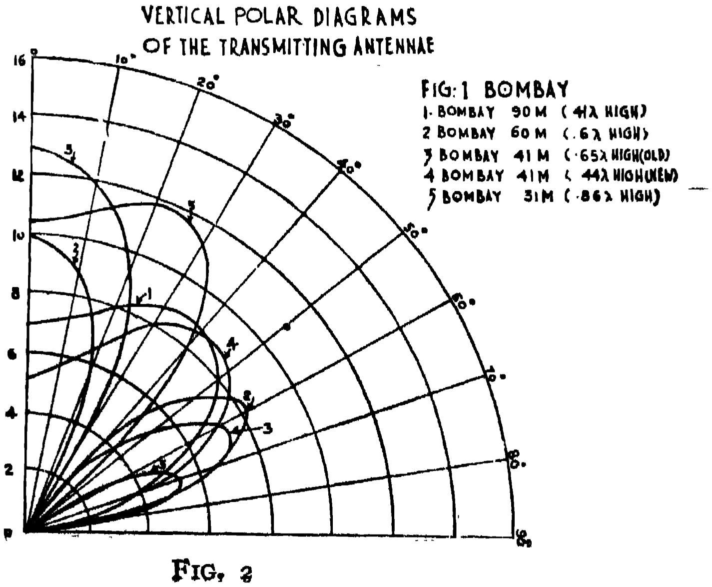


FIG. 2

TABLE I

Transmission No.	Transmission between—	Working wave-length in metres	Height of transmitting antenna	Period of measurements	Time of measurements	Average down-coming angle (measured) to the horizontal	Order of hop	Strongest hop	Layer governing the transmission
III Part—II	Bombay and Delhi	90	.41λ	March— April '41	Night	44° 56°	2nd hop 3rd hop	3rd hop	F - Layer
,,	,,	60	.6λ	April '41	,,	27° 46°	1st hop 2nd hop	1st hop	F—Layer
III Part—I	,,	60	6λ	March— April '41	Early evening	8° 19°	1st hop 2nd hop	2nd hop in March 1st hop in April	E—Layer
,,	,,	41	.65λ	April '41	,,	46°	2nd hop	2nd hop	F—Layer
II	,,	31	.86λ	May '41	Noon	22°	2nd hop	2nd hop	E—Layer
,,	,,	41	.44λ	Oct.— Nov. '41	,,	21° 40° 47° 59°	1st hop 2nd hop 3rd hop 4th hop	2nd hop	F2—Layer
Trans. I	,,	41	.65λ and .44λ	August— Nov. '41	Morning	21° 38° 53° 63°	1st hop 2nd hop 3rd hop 4th hop	1st & 2nd hops with the higher antenna, and 2nd & 3rd hops with the lower antenna.	F—Layer
Trans. III (Part—II)	Madras and Delhi	90	.49λ	March— April '41	Night	30° 45°	2nd hop 3rd hop	2nd & 3rd hops	F—Layer
	,,	60	.71λ	April '41	,,	17½° 45° 52° 56°	1st hop 3rd hop 4th hop 5th hop	1st hop	F—Layer

TABLE I (*contd.*)

Transmission No.	Transmission between—	Working wave-length in metres	Height of transmitting antenna	Period of measurements	Time of measurements	Average down-coming angle (measured) to the horizontal	Order of hop	Strongest hop	Layer governing the transmission
Trans. III (Part—I)	Madras and Delhi	60	.71λ	March—April '41	Early evening	9°.75 19°	2nd hop 3rd hop	2nd hop in April 3rd hop in March	E—Layer
	,,	41	.56λ	April '41	,,	35° 46°	2nd hop 3rd hop	2nd hop	F_2—Layer
Trans. I	,,	41	.56λ .44λ	August—Nov. '41	Morning 7-30 A.M.	8° 24° 35° 45° 56°	1st hop 2nd hop 3rd hop 4th hop 5th hop	3rd hop	F—Layer
					Morning 9 A.M.	8° 22° 44° 55°	1st hop 2nd hop 3rd hop 4th hop	3rd hop	F_1—Layer F_2—Layer

TABLE II*

Station	Transmission I		Transmission II		Transmission III				Period of operation
					Part I		Part II		
	Wave-length in metres	Duration	Wave-length in metres	Duration	Wave-length	Duration	Wave-length	Duration	
		I. S. T.		I. S. T.	Metres	I. S. T.	Metres	I. S. T.	
Bombay	41.44	0800-1000	31.4λ	1230-1425	61.48	1700-1915	89.15	1930-2245	1st November, 1940 to 15th April, 1941.
	,,	0730-0930	,,	,,	41.44	,,	61.48	,,	16th April, 1941 to 15th May, 1941.
	,,	,,	41.44λ	,,	,,	,,	,,	,,	16th May, 1941 to 15th October, 1941.
	,,	0800-1000	,,	,,	61.48	1615-1915	89.15	,,	16th October, 1941 to date
Madras	41.27	0730-0900	31.35λ	1330-1500	60.98	1600-1845	87.34	1900-2230	1st November, 1940 to 15th April, 1941
	,,	,,	,,	,,	41.27	,,	60.98	,,	16th April, 1941 to 15th May, 1941.
	,,	,,	41.27λ	,,	,,	,,	,,	,,	16th May, 1941 to 15th October, 1941
	,,	,,	,,	1300-1500	60.98	,,	87.34	,,	16th October, 1941 to date.

* Please note that the I.S.T. referred to is 5½ hours ahead of G.M.T.

and the downcoming ray of maximum energy are also indicated in this table. As mentioned earlier, these measurements were mostly on pulse signals. Special pulse transmissions were radiated for about 15 minutes' duration before the commencement of and soon after the close of any particular transmission. Table II gives the details of the transmission hours and the wave-lengths in the case of Bombay and Madras stations of All-India Radio on which the measurements were conducted. From the results arrived at on the pulse transmissions that were radiated just before and just after a particular transmission, the mode of propagation that prevailed during the actual transmission is deduced.

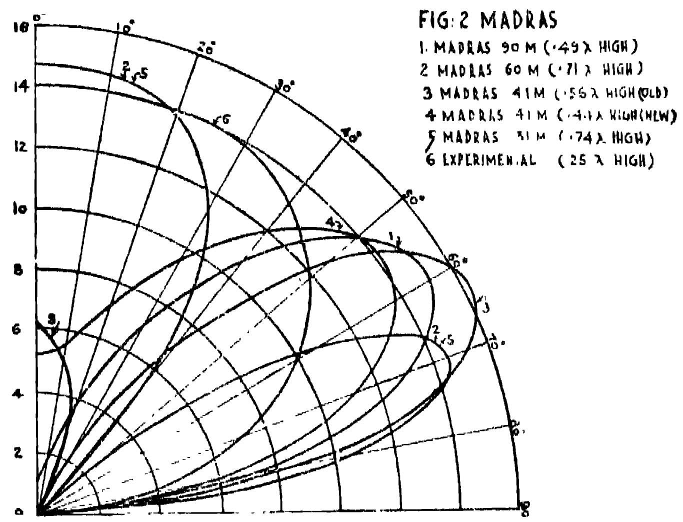


FIG. 3

In considering propagation between any two points, it is very necessary to know the state of the ionosphere, such as the ionic densities and the layer heights, the distance between the two places, the transmitting and receiving antennae characteristics and the working wave-lengths. The working wave-lengths are given in Table II. Table III gives the details of the transmitting antennae. The transmitting antenna in all cases is a horizontal dipole aerial at different heights above the ground. The vertical polar diagrams of these aerials as calculated and drawn for the Delhi bearing are given in Figs. 2 and 3. The distance between Bombay and Delhi is 1,145 kms. and between Madras and Delhi is 1,971 kms. on the great-circle path. Such of the ionosphere data that are available are given in the form of graphs III, IV, V and VI (Figs. 6 and 7).

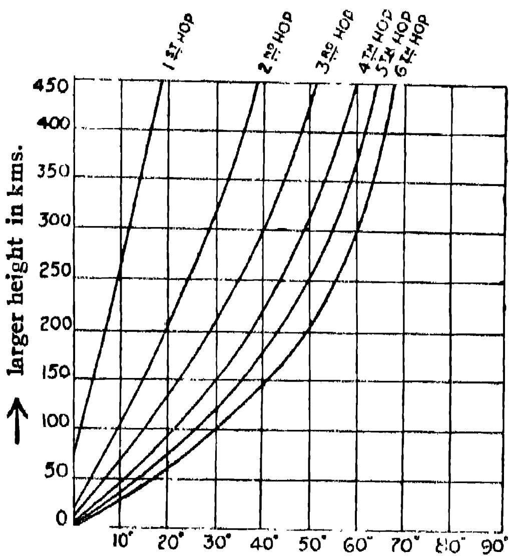
For facilitation of discussion, the results for each transmission are taken up separately. Thus the results fall under 4 parts: (*i*) Transmission I (morning); (*ii*) Transmission II (noon); (*iii*) Transmission III, part 1 (early evening); and (*iv*) Transmission III, part 2 (night).

In order to follow the sequence of the measurements made, the results for the night transmission are presented first.

TRANSMISSION III (PART 2)

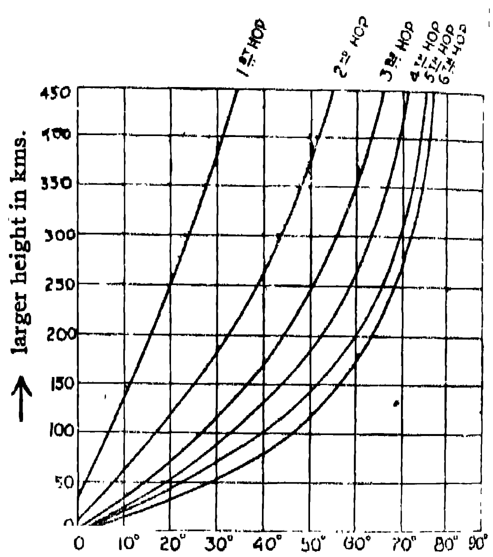
As would be expected, the propagation at this time is *via* the F-layer.

The two stations, Bombay and Madras, on which the measurements were conducted, were operating in the 90 metre band for the winter of 1940-41 and in the 60 metre band for the summer of 1941. The details of the change-over appear in Table II.



→ downcoming angle (measured to the horizontal)

FIG. 4



downcoming angle (measured to the horizontal)

FIG. 5

TABLE III

Station	Wave-length	Height of transmitting antenna in terms of λ	Bearing of transmitting antenna	Bearing of the station from Delhi	Angle between the directions of antenna and Delhi
Bombay	31.4 m.	.86λ	North-South	203°.27 E of N.	23°.27
	41.44 m.	.65λ (old)	,,	,,	,,
	,,	.44λ (new)	,,	,,	,,
	61.48 m.	·6λ	,,	,,	,,
	89.15 m.	.41λ	,,	,,	,,
Madras	31.35 m.	.74λ	75° E of N.	168°.85 E of N.	86°.15
	41.27 m.	.56λ (old)	,,	,,	,,
	,,	.44λ (new)	,,	,,	,,
	60.98 m.	.71λ	,,	,,	,,
	87.34 m.	.49λ	,,	,,	,,

During 90 metre operation, a typical pulse pattern obtained in the case of Bombay is to be seen in pattern No. 1, plate IX, and the case of Madras is to be seen in pattern No. 1, plate X. It will be seen that there are several component pulses, or 'returns,' in each case. They represent successive multiple reflections from the F-layer. The downcoming angles for each of these returns were obtained. On a reference to Table I, it will be seen that in the case of Bombay, the second return was giving an angle of 44° to the horizontal while the third return gave an angle of 56°. In order to know the layer height from these angles, reference is to be made to graph I (Fig. 4), which is drawn to show the down

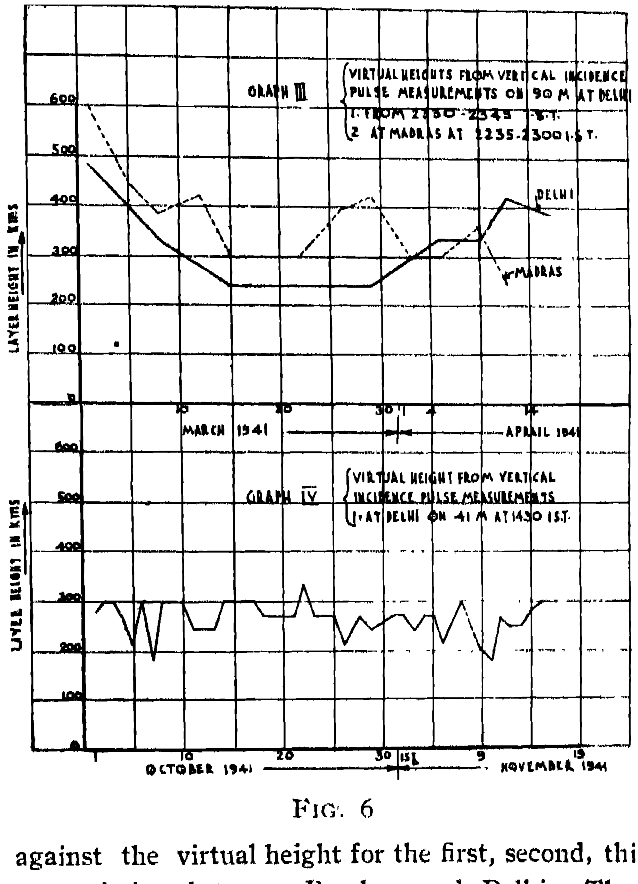


FIG. 6

coming angle against the virtual height for the first, second, third, fourth, fifth and sixth hop transmission between Bombay and Delhi. The virtual height of the layer comes out to be of the order of 290 km. In the case of Madras, the downcoming angles obtained were 33° and 45° corresponding to the second, and third returns in the pulse-pattern. On a reference to graph II (Fig. 5) drawn, for transmission between Madras and Delhi, the layer height comes out to be 350 km. An idea of the nature of the F-layer height is to be obtained from that recorded at this time at Madras and Delhi working on 90 metre wave. This is given in graph III (Fig. 6). The average layer height at Delhi is nearly 300 km. while at Madras it is of the order of 350 km.

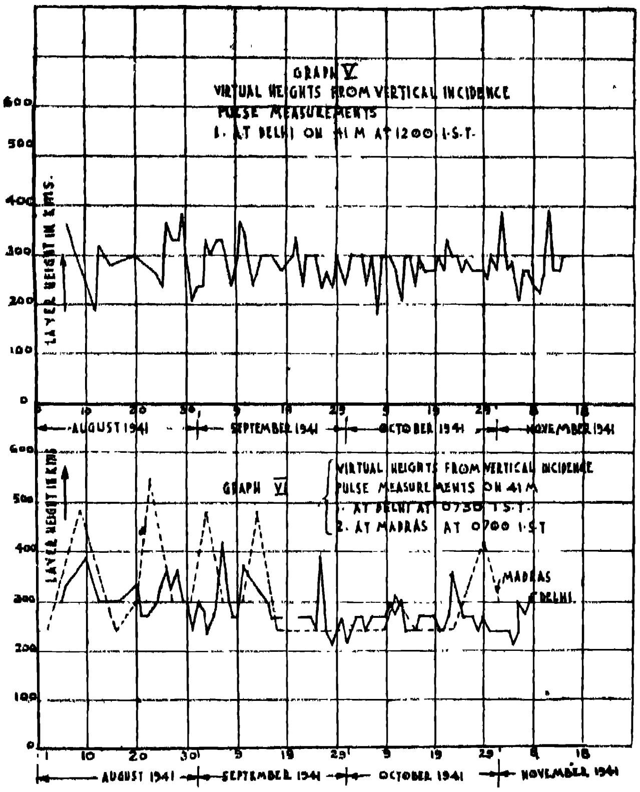
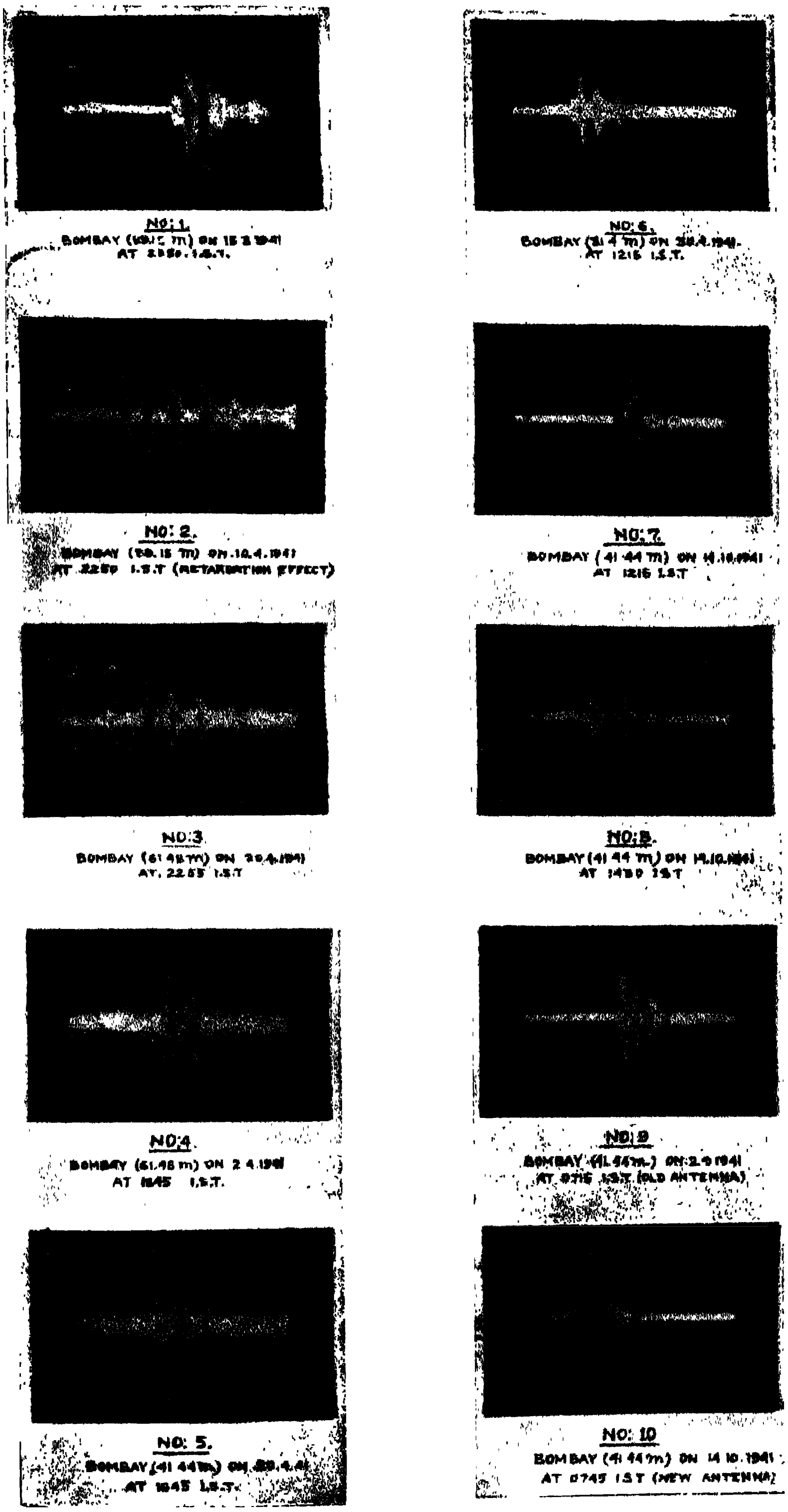


FIG 7

On a study of the pulse patterns it will be seen that in the cases of Bombay and Madras, the third hop is the strongest. During the several observations made, it was found that it was either the second hop or the third hop that was the strongest. It may be remembered that the amplitudes of these returns were subject to 'fading.' They would vary considerably and irregularly. Seldom was the 1st hop strong. The reason for this is not far to seek. It is due to the characteristics of the transmitting and the receiving antennae used. The transmitting antenna is not radiating at the angle required for 1st hop propagation and the receiving aerial is not picking up so well at the ~~1st~~ hop angle as at the 2nd and 3rd hop angles. The result observed is the product of the both.

In the case of Bombay for F-layer transmission the downcoming angles are 24°.5 for 1st hop, 44° for the 2nd hop and 56° for 3rd hop. These are read off from graph I (Fig. 4) for a virtual height of 300 km. The relative radiation amplitudes for the transmitting antenna given in Fig. 2 are 5.3 for 1st hop, 8.7 for the 2nd hop, and 9 for the 3rd hop, while the pick-up figures of the receiving aerial are 5, 8.2 and 9.8, respectively. As a result of these, the received signal amplitudes, being proportional to the products of these, are 26.5, 71.3 and 88.2 for 1st, 2nd and 3rd hops respectively. Allowing for the correction to be made for



Typical pulse-pattern photographs

spreading and attenuation (the latter however being usually negligible at the time when these measurements are made) it can be shown that the 1st hop would be considerably weaker than the 2nd and 3rd hops.

Similarly in the case of Madras (Fig. 3), the resultant amplitudes work out to be 17.6, 70.5 and 92.4 for 1st, 2nd and 3rd hops respectively. From this it is clear why 2nd and 3rd hops are stronger in the cases of both Bombay and Madras.

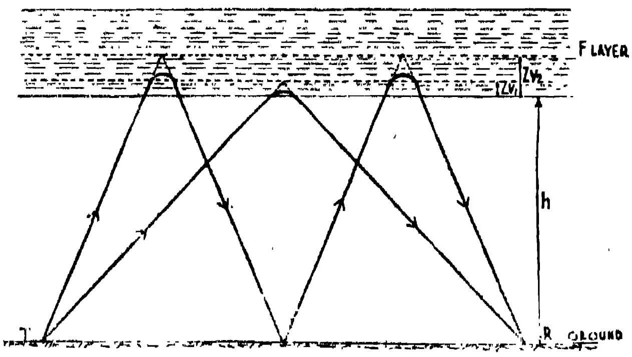
The vital part the antenna plays is brought out in the following results: Aerial change-over tests were carried out at the Madras transmitter using a high and a low aerial alternately. The test was carried out during the pulse transmission. When the higher aerial (.49λ high) was used the maximum energy was received at an angle of 30° to the horizontal and it corresponded to the 2nd hop from the F-layer, while with the lower aerial (.25λ high) the maximum energy received was at 58° and corresponded to 5th hop from F. Turning to the polar diagrams of the two transmitting aerials, it will be seen that in the case of higher aerial, maximum radiation is at about 34° to the horizontal, while with the lower aerial, the maximum radiation is at a much higher angle.

When Madras and Bombay started operating on 60 m. band for the summer of 1941, the same 90 m. aerial was used, thus raising the height of the transmitting antenna in terms of λ (wave-length), and favouring low angle radiation. It was then predicted that 1st hop should be the strongest and, as will be seen later, this was the case. When Madras and Bombay stations lowered the height of their transmitting antenna on 41 m. to .44λ in the day transmission, the immediate effect was the weakening or disappearance of the first hop.

There are a few interesting observations to be noted here. On the 4th of March, 1941, at 2230 I.S.T. Bombay 90 m. carrier was observed to be fading as a rapid flutter. This was unusual, but the downcoming angle was all the time very steady, indicating a single-ray transmission. The angle was 32° and represents 1st hop from F, the virtual height being 407 km. The 4th of March, 1941, happens to be a magnetically disturbed day, though reported to be of slight intensity. The low ionization density and high layer height would tend to decrease maximum usable frequency. This may explain why the 2nd and 3rd hops which are usually the strongest were absent on this date. The agitation of the signal observed is probably due to a similar state of agitation of the ionosphere to be expected on a magnetically disturbed day.

THE VIRTUAL HEIGHT PARADOX

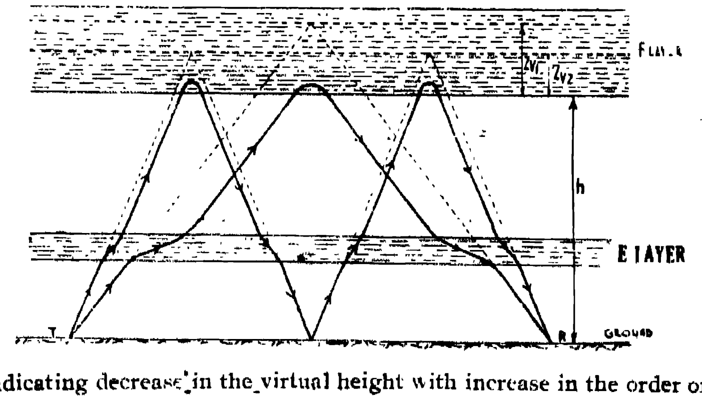
In a multi-hop transmission, the virtual height of the layer from which reflections take place would increase as the order of the hop increases, as shown in Fig. 8. The results on Bombay and Madras stations working in the 90 m. band usually conformed to this. However, at the beginning of April, an unusual phenomenon was observed on Bombay pulse-patterns. Fig. 2, plate IX, gives such a type of pattern. It will be seen that as against Fig. 1, plate IX, which is the usual pulse-pattern, the returns are very much separated, indicating greater



Indicating the increase of virtual height with the increase in the order of the hop

FIG. 8

time delays. The downcoming angles obtained for such returns showed that the virtual height decreases as the order of hop increases. For instance, the results on the 10th April, 1941, showed that the 1st hop is reflected from a virtual height of 500 km., the 2nd hop from 440 km. and 3rd hop from 393 km. This is in variance with the established notions. As an explanation it is suggested that a deflecting layer in the transmission path, such as the residual E-layer that could have been present at the time of measurement, would be responsible for such a phenomenon. In Fig. 9 the transmission path and the virtual height are diagrammatically shown based upon the equivalence theorem for the plane earth. It will be seen from the diagram that the virtual height for the 2nd hop is actually lower than that for the 1st hop. In the presence of a deflecting layer in the transmission path, the amount of deviation produced is dependent upon the angle of incidence of the ray. A vertically incident ray does not suffer



Indicating decrease in the virtual height with increase in the order of hop in the presence of an intervening ionised layer

FIG. 9

any deviation, whereas the greater the obliquity of the incident ray the greater will be the deviation. The greater the deviation the greater is the virtual height. Thus the 1st hop is affected more than the 2nd hop which in turn is affected more than the 3rd hop.

Another effect of the intervening layer is its effect on the energy distribution in the various component rays. Referring to the pulse-pattern No. 2, plate IX, again, it will be noted that the first four hops are of the same order of amplitude. The first hop which on normal days was very much weaker than the second and third hops, is now equal in amplitude. It was shown earlier that the amplitudes are in the ratio of 21, 71 and 88 on an assumption of no attenuation being experienced. However, with the presence of the intervening E-layer, this factor cannot be ignored. The attenuation suffered will be greater, the greater the number of hops. This tends to equalize the relative amplitudes. Thus it will be seen that the effects of intervening ionized strata are felt in the time-delays, in the energy distribution, and in the values of the downcoming angles of the component waves. Here the effects are only mentioned. It allows a study on a quantitative basis.

On the 16th of April, 1941, Bombay and Madras changed over to the 60 metre band. As entered in Table I, the results show that the propagation is taking place by multiple reflections from the F-layer. In the case of Bombay the downcoming angles were 27° for the first hop and 46° for the 2nd hop. These give virtual heights of 335 km. and 317 km. respectively. The lowering of the virtual height as the order of the hop increases is again due to intervening E-layer. In the case of Madras the angles are 17°.5, 45°, 52°, 56° for the first, third, fourth and fifth hops respectively, giving virtual heights of 410 km., 357 km., 337 km. and 315 km., respectively. This marked progessive lowering of the virtual height is once again the effect of the E-layer.

As the pulse-patterns reveal (No. 3, plate IX, and No. 2, plate X), in either case it is the first hop which gives the maximum energy. The reason, as was predicted earlier, was due to the transmitting antennae favouring low-angle radiation.

TRANSMISSION III, PART I (EARLY EVENING)

The two reference stations were operating on the 60 metre band during the winter of 1940-41, and on the 41 metre band during the summer of 1941.

During winter, a typical pulse-pattern obtained on pulse-signals radiated from Bombay just before the commencement of the actual transmission is given in pattern No. 4, plate IX. Two returns were usually present. They are the first and the second hops from the E-layer. The first hop gave an angle of 8° while the second gave an angle of 19°. The virtual heights work out to be 103 km., in either case.

The question which now arises is whether E-layer transmission between Bombay and Delhi is possible at this time (5 p.m.) and whether the transmitting antenna gives appreciable radiation at such low angles. Although no experimental data for E-layer critical frequencies are available for this period, fairly reliable computation can be made by the use of Chapman's formula

$$\frac{f_{E_1}}{f_{E_2}} = \left(\frac{\cos Z_1}{\cos Z_2}\right)^{\frac{1}{4}}$$

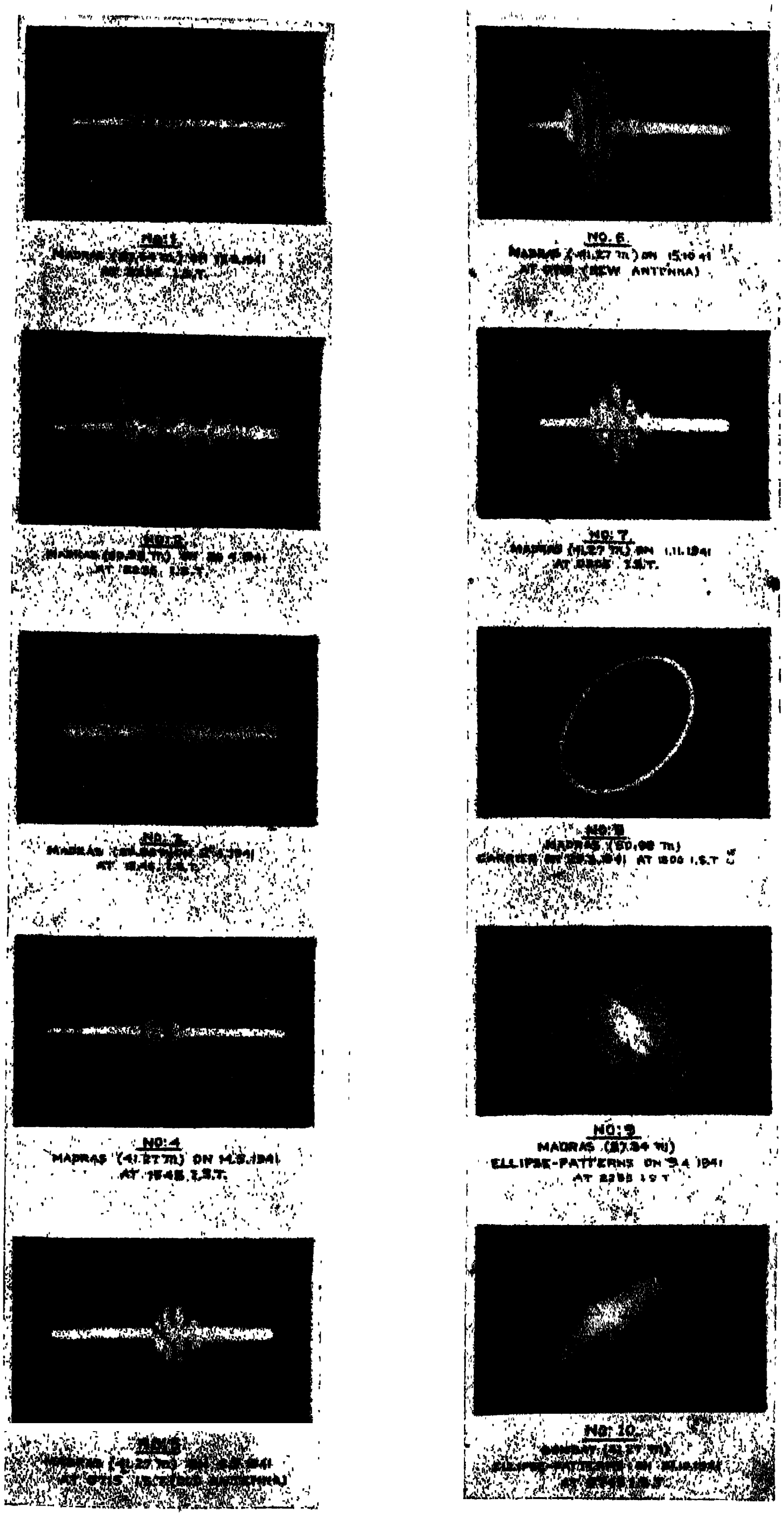
(where Z_1 and Z_2 are the Sun's zenithal angles) and the Washington critical frequency data available for this period. Calculated maximum usable frequencies for the months of March and April, 1941, work out to be 9.1, 5 and 3.8 Mc/s for the first, second and third hop propagation during the month of March and 9.6, 5.3 and 4 Mc/s, respectively for the month of April, 1941. Thus the first and the second hop transmission *via* the E-layer may be possible. There is a certain amount of radiation at these angles, but the radiation is low. This would suggest that the signals are to be expected to be poor, which was actually the case. Radiation at higher angles was useless as far as the particular receiving point was concerned, as such signals would be badly attenuated on their passage through the E-layer.

In March, the second hop was observed to be the stronger while in April the first hop was the stronger. The pulse-pattern given in plate IX is for April. There are two factors to be considered in this connection. One is the radiation at these angles and the other is the attenuation in the lower regions such as the D region. The radiation at the second hop angle is greater, but so are the attenuation losses. As the attenuation losses would be greater in April it would appear that the balance is in favour of second hop in March and first hop in April.

The results presented above refer only to the propagation conditions prevailing at the beginning of the transmission. There is unfortunately insufficient interval between part I and part II of transmission III for special pulse transmission in order to study the propagation conditions at the end of part I of transmission III.

In the case of Madras, there was usually a solitary return present, as will be seen from pulse-pattern No. 3, plate X. The carrier was found to be exceedingly steady and the ellipse on the C.R.O. showed a steady angle all the time. Such an ellipse is illustrated in pattern No. 8, plate X. The transmission is evidently by a single ray. The downcoming angle was measured to be 19° in March, 1941, which is probably E-layer transmission.

Though no experimental data for E-layer critical frequencies are available for this period, on computation it was found that the first, second and the third hop propagation *via* the E-layer was possible. Added to this possibility, is the suitability of the transmitting aerial. The transmitting aerial was 0.71λ high, giving fairly low-angle radiation. Referring to Fig. 5, the downcoming angles for propagation *via* the E-layer come out to be 1°.2 for 1st hop, 9°.1 for 2nd hop



Typical pulse-pattern photographs

and 15°.1 for 3rd hop. The relative intensities in these directions, as read from the polar diagram in Fig. 3, are nil, 10.6 and 14.4, respectively. Transmission by 1st hop being ruled out, transmission by either 2nd or 3rd hop is possible.

Supporting the E-layer transmission, there is a certain amount of practical evidence too. Strong echoes from E-layer were observed on vertical incidence pulse measurements carried out on the 60 m. band at Delhi on the 2nd April and at Madras on the 9th April, 1941, at the time of these measurements. They were not of sporadic nature but they were strong and persistent echoes—which would suggest a probability of transmission by E-layer on these two days. The same characteristics of the received signal, *i.e.*, steady though poor, were observed on those two days as on other days, indicating no difference in the mode of propagation. It is, therefore, deduced that the transmission on all the days is probably by E.

As stated above, the downcoming angle in March, 1941, was 19°. This works out to be 3rd hop from E. In April, the conditions were not as steady as in March. The downcoming angle came out to be 9°.75 which works out to be 2nd hop from the E-layer. Here again the two factors, the radiation and the attenuation, seemed to have come into consideration.

As in the case of Bombay, these results presented above refer only to the beginning of the evening transmission. Later in the transmission, the steady ellipses on carrier slowly gave place to more unsteady ones and by the close of the transmission, the ellipses were found to be highly unsteady, indicating the presence of two or more component waves. It is to be expected that the E-layer propagation gave way to the F-layer propagation.

On the 16th of April, 1941, both Bombay and Madras changed over to the 41 metre band for the summer.

Madras begins its transmission at 4 p.m. The signal on the pulses was found to be extremely poor. In general the pulse-patterns were composed of 3 groups of returns well separated as seen in pattern No. IV, plate X. Generally the 2nd group was found to be the strongest. The downcoming angle came out to be 35°. On these days when the 2nd group was found to be the strongest in the pulse pattern measurements made on the carrier soon afterwards, when full power was put on for the actual transmission, the angle came out to be 34°. The angle for the 3rd group was also obtained and it came out to be 46°. Thus we have a pattern of three returns, the 2nd giving an angle of 34° and the 3rd an angle of 46° ; 34° corresponds to 2nd hop from a layer height of 370 km. and 46° corresponds to 3rd hop from a virtual layer height of 370 km. again. On this basis we may assume that the three returns observed in the pulse pattern are the 1st, 2nd and 3rd hops from F_2 layer. These returns instead of being in the form of single pulses are in the form of groups. The groups are formed due to the angular spread in the vertical plane, which may be due to scattering or irregular reflections in the ionized layer. Theoretical considerations show a possibility of 2nd hop propagation *via* the E-layer. No results were obtained to confirm this.

Bombay starts its transmission at 5 p.m. The special pulse transmission, preceding this, usually gave a pulse-pattern of four returns out of which the 2nd was observed to be the strongest (No. 5, plate IX). The angle corresponding to this comes out to be $46°$ as shown in table I, and fits in as 2nd hop from a layer of a virtual height of 317 km. The delays between the successive returns appear to show that they are the successive hops from F-layer. The maximum usable frequencies for transmission *via* the E-layer show that that only one hop transmission would be possible. However, there is no radiation from the transmitting antenna at this angle as can be seen from the polar diagram. As at 5 p.m. it is difficult to show clear demarcation between F_1- and F_2-layers, we may say that the transmission is by F-layer.

Summarising the results for the beginning of transmission III, it would appear that propagation on 60 metres is *via* E-layer, while in the case of 41 metre transmissions, it is probably *via* F_2 in the case of Madras and F in the case of Bombay.

TRANSMISSION II (NOON)

In the winter months of 1940-41, and till the 15th May, 1941, Bombay and Madras were working on 31 metres and changed over to 41 metres on the 16th May, 1941.

The pulse transmissions from Bombay, preceding and succeeding the actual transmission, gave three returns as seen in pulse-pattern No. 6 in plate IX. The second was always the strongest. It was usually several times stronger than either the 1st or 3rd. The average downcoming angle for the 2nd return came out to be $22°$ to the horizontal, which represents 2nd hop transmission from E at a height of 125 km. The time-delays between the first two returns in the pulse-pattern also go to show that the transmission is by E-layer.

The theoretical considerations based on critical frequencies show that one hop and two hop transmission *via* the E-layer is the most probable mode of propagation.

It was stated above that the 2nd hop giving an angle of $22°$ was several times stronger than either the 1st or the 3rd. The reason lies in the characteristics of the transmitting antenna. The polar diagram given in Fig. 2 shows that most of the energy is transmitted at very high angles. But for a small lobe there is no energy until we reach $50°$ to the horizontal. The small lobe gives a maximum at $20°$ to the horizontal which was nearly the angle that was obtained for the second return. All the high-angle radiation was useless as far as the receiving point was concerned. Such high-angle radiation could be received as a 7th or 8th hop from E or 3rd or 4th hop from F_2. Neither of these would, however, reach the receiving place, for they would be attenuated away.

No definite results could be obtained on Madras during transmission II due to the poor signal strength.

After the introduction of 41 metres for noon transmission, results were obtained in the case of Bombay during the months of October and November, 1941. The pulse transmission preceding and succeeding the actual transmission usually gave four returns (pulse-pattern Nos. 7 and 8, plate IX). The average downcoming angles obtained were 21°, 40°, 47° and 59° corresponding to the first four returns. They work out to be 1st, 2nd, 3rd and 4th hop from F_2 layer at a virtual height of nearly 250 km. E-layer transmission by one hop could be possible, but for little energy being radiated by the transmitting antenna at this angle. Data are available from the vertical incidence pulse measurements carried out at Delhi before the commencement and after the end of noon transmission that give an average layer height of about 280 km at 12.00 noon and 270 km. at 14.30 hrs. The day-to-day variations in height are shown in graphs IV and V (Figs. 6 and 7). For oblique incidence the layer height as expected was obtained to be lower than for vertical incidence.

Summarising the results for the noon transmission, we find that the transmission between Bombay and Delhi on 31 metres is *via* the E-layer in May, 1941, and by F2-layer in October, 1941, when the working wave-length was 41 metres. Taking all the factors into consideration we find once again that the practical and theoretical modes agree.

TRANSMISSION I (MORNING)

Bombay and Madras operated on 41 metres during transmission I for the entire period under review. The results in the case of Bombay, both before and after the transmission, work out to be multiple hops from F-layer. They fairly closely follow mirror-like reflections. The average downcoming angles were 21°, 38°, 53° and 63° for the 1st, 2nd, 3rd and 4th hops respectively. The virtual height is nearly 250 km. Vertical incidence pulse measurements carried out before the commencement of transmission show considerable variations in the virtual heights recorded as can be seen from graph VI (Fig. 7). These variations are due to the working frequency being close to the critical frequency. The average layer height in the month of August to the middle of September is approximately of the order of 300 km., and from the middle of September till the middle of November is of the order of 260 km. Thus once again the layer heights obtained by the oblique incidence measurements are lower. Bombay was originally using a transmitting aerial 0.65λ above ground and changed over to an aerial 0.44λ above ground on the 8th of October, 1941. A simultaneous change was noticed. First hop, which was quite strong, became considerably weaker. Fig. 9, plate IX, shows the pulse-pattern observed before the aerial change-over and Fig. 10, plate IX, shows the pulse-pattern after the change-over. The polar diagram for the old and new transmitting antennae (Figs. 2 and 3) bear out the results that were obtained. When the higher aerial was used, the 1st and 2nd hops were observed to be quite strong and the 3rd hop was considerably weak. With the lower aerial 1st hop was weak and the 2nd and the 3rd hops were strong.

In the case of Madras, multiple reflections from F-layer during the pulse transmission preceding the morning transmission were observed. The downcoming angles measured were 8°, 24°, 35°, 45° and 56° for the first five hops. The virtual heights came out to be 220, 247, 250, 260 and 310 km. respectively. The ascending order in the virtual heights is to be expected. As the working frequency approaches the maximum usable frequency, the virtual height increases. It was observed that usually the 3rd hop was the strongest, both in the case of the old and new antennae. Typical pulse-patterns obtained are given in plate X, Nos. 5 and 6. The transmitting aerial was originally 0.56λ above ground and it was changed over to 0.44λ on the 5th October, 1941. After the change-over the 1st hop almost disappeared. Polar diagrams of the old and new antennae are given in Figs. 2 and 3, which show that the new aerial hardly gives any radiation at the 1st hop angle

The pulse transmission following soon after the close of the morning transmission usually gave five returns. The first two reflections are close together while the 3rd and the 4th are well separated. The downcoming angles obtained are 8° and 22° for the 1st and 2ndreturns. The 3rd return gave a downcoming angle of 44° while the 4th gave an angle of 55°. They correspond to 1st hop from 220 km., 2nd hop from 220 km., 3rd hop from 350 km., and 4th hop from 375 km. A sudden jump in the virtual height for the 3rd and 4th hops is to be noticed. These measurements were taken at about 9 A.M. The results appear to show that the first two returns observed are the 1st and 2nd hops from F1 layer while the 3rd and 4th returns are the 3rd and 4th hops from the F2-layer. The basis for such a transmission is this : At 9 A.M. in October, 1941, the F1-layer critical frequency is such that only one-hop and two-hop transmission between Madras and Delhi is possible. Radiation at higher angles will penetrate the F1-layer and will be reflected from the F2-layer. It seems that the transmission between Madras and Delhi is by both F1- and F2-layers. The lower angles are reflected from F1-layer while higher angles are reflected from F2-layer.

Summarising the results for the morning transmission, we find that the multiple reflections from F-layer observed are in agreement with the theory. The results in the case of Madras for the end of the transmission suggest propagation both *via* F1- and F2-layers.

CONCLUSIONS

A few general conclusions that may be drawn from the present study are as follows :—

(1) Multiple reflection phenomenon is involved in the type of wireless propagation that was investigated.

(2) Presence of the E-layer and other intervening absorbing strata has the effect of reducing the number and strength of the components that comprise a downcoming wave. Such strata also introduce large deviations in the ray path, as a result of which the downcoming angles are enhanced.

(3) In the absence of any intervening layers, as for instance in the early mornings and nights, the downcoming angles agree fairly with the values calculated on the basis of simple mirror-like reflections

(4) Under the conditions, as postulated in (3) above, a knowledge of the state of the ionisation of the ionosphere, the working wave-length, the characteristics of the transmitting and receiving antennae, etc., could be used for making reliable predictions of the type of propagation that may prevail in the case of short-distance short-wave propagation.

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